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ONE POSSIBLE MECHANISM FOR THE FORMATION OF INHOMOGENEITIES IN INTERPLANETARY PLASMA

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ABSTRACT. One of the possible mechanisms for formation of an inhomogeneous structure of interplanetary plasma is under discussion. The mechanism is due to instability of electron flows moving on helical trajectories along force lines of the interplanetary magnetic field. Characteristic dimensions of unstable perturbations l are shown to be located within the range of $1.2 \cdot 10^7 - 2 \cdot 10^8$ cm.

1. The existence of electron density inhomogeneities in the interplanetary plasma was established in 1954 [1, 2] using the radioastronomical method ("transmission" method). After quarks were discovered in 1963, it became possible to use the method of radioscintillation of sources in studying interplanetary inhomogeneities. Observational data on the scintillation period and the velocity of the inhomogeneities, when compared with data obtained by the transmission method, show that the characteristic dimensions of the inhomogeneities l range between $10^7 - 10^8$ cm [3 - 6]. /2048*

Several authors [7, 8] have repeatedly attempted to explain the inhomogeneities in the interplanetary plasma by the development of a different kind of instability. Thus, for example, an attempt was made in [8] to connect the anistropic instability of a magnetized plasma with observed inhomogeneities. A different mechanism for a plasma instability will be investigated below, which may be connected with the characteristic dimensions of the observed inhomogeneities.

Research with rockets has made it possible in recent years to obtain many important data on solar electron fluxes [9 - 11]. For example, after analyzing data obtained by the satellites "IMP-1" and "IMP-3", it was found in [10] that

* Numbers in the margin indicate pagination in the original foreign text.

there are electron fluxes with electron energies exceeding 40 kev in interplanetary space. An analysis of data obtained by means of the rocket "MARINER-4" led to the conclusion that the increased electron intensity in interplanetary space is caused by their pulse emission from the solar atmosphere [11]. These data show that electron fluxes moving from the Sun to the Earth are connected with the force lines of the interplanetary magnetic field. Therefore, in the general case the electron fluxes are curvilinear. It will be shown in this article that allowance for the electron flux curvilinearity leads to instability phenomena which may produce the inhomogeneous structure of the interplanetary plasma.

2. In order to describe the wave processes in the electron flux, we shall use the relativistic equation of motion for an electron liquid which is balanced in terms of charge and current.

$$\frac{d\mathbf{p}}{dt} = -e\left(\mathbf{E} + \frac{1}{c}\mathbf{v}\times\mathbf{H}\right), \quad \mathbf{p} = \frac{m\mathbf{v}}{\sqrt{1-\frac{v^2}{c^2}}} \tag{1}$$

and the Maxwell equations for an electromagnetic field /2049

$$\begin{gathered} \operatorname{rot}\mathbf{H} = \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} - \frac{4\pi e}{c}\varrho\mathbf{v}, \quad \operatorname{rot}\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{H}}{\partial t}, \\ \operatorname{div}\mathbf{E} = -4\pi e(\varrho - \varrho_0), \quad \operatorname{div}\mathbf{H} = 0, \end{gathered} \tag{2}$$

where ρ_0 is the density of equalizing ions which are assumed to be stationary. The notation is the same as usual.

Assuming an external magnetic field H_0 which is directed along the z axis, we may readily establish that the following expressions

$$v_{x0} = -v_\perp \sin\frac{\omega_H}{v_\parallel}z, \quad v_{y0} = v_\perp \cos\frac{\omega_H}{v_\parallel}z, \quad v_z = v_\parallel \tag{3}$$

where $\omega_H = \frac{eH_0}{mc}\left(1 - \frac{v_\perp^2 + v_\parallel^2}{c^2}\right)^{1/2}$, is the steady-state solution of Equation I in in the absence of an electromagnetic field. As follows from (3), the flux which we are investigating is a semi-helical flux of electrons with identical initial phases.

The dispersion equation for waves propagated in a semi-helical flux along the magnetic field H_0 was obtained in [12], and it may be represented in the following form

$$\Omega^2[\Omega^2-\omega_b^2(1-\beta_\parallel^2)]\left[\omega^2-\left(kc-\frac{\omega_H}{\beta_\parallel}\right)^2\right]\left[\omega^2-\left(kc+\frac{\omega_H}{\beta_\parallel}\right)^2\right]=$$
$$=\frac{\omega_b^2}{2}\left\{\left[\left(kc-\frac{\omega_H}{\beta_\parallel}\right)^2-\omega^2\right]P_1+\left[\left(kc+\frac{\omega_H}{\beta_\parallel}\right)^2-\omega^2\right]P_2-2\omega_b^2P_3-2\omega_b^4P_4\right\}, \tag{4}$$

where

$$\Omega=\omega-kv_\parallel,\ \omega_b^2=4\pi e^2\varrho_0/m\varkappa,\ q=\beta_\perp/\beta_\parallel,\ \beta_{\parallel,\perp}=v_{\parallel,\perp}/c,\ \varkappa=(1-\beta_\parallel^2-\beta_\perp^2)^{-1/2},$$
$$P_1=q^2(\omega\beta_\parallel^2-kv_\parallel-\omega_H)\{\Omega^2[kv_\parallel+\omega_H(1+\varkappa^2\beta_\parallel^2)]-\omega_b^2\beta_\parallel^2(\Omega+\omega_H\varkappa^2\beta_\perp^2)\}-$$
$$-[\Omega^2-\omega_b^2(1-\beta_\parallel^2)]\left[\omega_H\varkappa^2\beta_\perp^2(\Omega-\omega\beta_\perp^2-\omega_H)+2\Omega\left(\Omega-\frac{\omega\beta_\perp^2}{2}-\omega_H\right)\right],$$
$$P_3=-\omega\omega_H^2kv_\parallel q^2\beta_\perp^2-kv_\parallel q^2\Omega[\Omega(\omega\beta_\parallel^2-kv_\parallel)-\omega_H^2]+$$
$$+\Omega^2[\Omega^2-\omega\Omega\beta_\perp^2-\omega_H^2]+q^2\omega\omega_H^2\Omega(1-\beta_\parallel^2)(1+\varkappa^2\beta_\parallel^2),\quad P_4=\frac{\omega_H^2-\Omega}{\varkappa^2}.$$

The quantity P_2 is obtained from P_1 by replacing ω_H by $-\omega_H$.

The dispersion equation obtained (4) is a polynomial of the eighth power with respect to ω. Since there is no analytical expression for the roots, a precise analysis of it in the general case is only possible by numerical methods. We shall make an approximate analysis in this work, assuming that ω^2_b is a small parameter.

We shall search for the solution of the dispersion equation (4) in the following form

$$\Omega=\omega-kv_\parallel=\gamma\omega_b. \tag{5}$$

Substituting (5) in (4) and retaining only terms of the lowest order with respect to ω^2_b, we obtain a biquadratic equation with respect to γ, whose solution /2050 has the following form

$$\gamma_{1,2,3,4} = \pm \frac{1}{\varkappa\sqrt{2}} \times$$

$$\times\left\{1 \pm \sqrt{1 - 4\omega_H^2\varkappa^2\beta_\perp^2\beta_\parallel^2 \frac{k^2v_\parallel^2 + \omega_H^2\varkappa^2}{[(kv_\parallel - \omega_H)^2 - (kv_\parallel\beta_\parallel)^2][(kv_\parallel + \omega_H)^2 - (kv_\parallel\beta_\parallel)^2]}}\right\}^{1/2} \tag{6}$$

It follows from the above formula that for

$$[(kv_\parallel - \omega_H)^2 - (kv_\parallel\beta_\parallel)^2][(kv_\parallel + \omega_H)^2 - (kv_\parallel\beta_\parallel)^2] < 0 \tag{7}$$

the two roots of γ will be complex conjugants, which according to (5) corresponds to an instability with the increment

$$\operatorname{Im}\omega = \omega_b \frac{\beta_\perp\omega_H\beta_\parallel (k^2v_\parallel^2 + \omega_H^2\varkappa^2)^{1/2}}{\{[(kv_\parallel\beta_\parallel)^2 - (kv_\parallel - \omega_H)^2][(kv_\parallel + \omega_H)^2 - (kv_\parallel\beta_\parallel)^2]\}^{1/2}}. \tag{8}$$

It follows from formula (7) that an instability occurs in the following wave vector interval

$$\frac{\omega_H/v_\parallel}{1+\beta_\parallel} < k < \frac{\omega_H/v_\parallel}{1-\beta_\parallel}. \tag{9}$$

It must be pointed out that the instability under consideration is caused by the relativistic nature of the electron motion.

The approximate solution of (6), and consequently of (8), does not hold in the vicinity of the points where the denominator $[(kv_\parallel - \omega_H)^2 - (kv_\parallel\beta_\parallel)^2][(kv_\parallel + \omega_H)^2 - (kv_\parallel\beta_\parallel)^2]$ vanishes. These points correspond to the synchronism of waves with the dispersion laws $\omega = kv_\parallel$ and $\omega = \pm\frac{\omega_H}{\beta_\parallel} \pm kc$. At these points, the approximate solution of (4) must be sought in another manner. For this purpose, Equation 4 may be re-written in the following form

$$(\omega - kv_{\parallel})^4\left[\omega \mp \frac{\omega_H}{\beta_{\parallel}} - kc\right] = \omega_b^2 K(\omega, k, \omega_b). \quad (10)$$

Since the right part is proportional to ω_b^2, for the approximate solution of (10) the coupling constant $K(\omega, k, \omega_b)$ may be calculated at the point of the synchronism $\omega_0 = \frac{\omega_H}{1 \pm \beta_{\parallel}}$, $k_0 = \frac{\omega_H/v_{\parallel}}{1 \pm \beta_{\parallel}}$. As a result of this, Equation 10 assumes the following form

$$(\omega - kv_{\parallel})^4\left[\omega \mp \left(\frac{\omega_H}{\beta_{\parallel}} - kc\right)\right] = -\frac{1}{4}\omega_b^4\omega_H\beta_{\perp}^2\left(1 \pm \beta_{\parallel} - \frac{1}{2}\beta_{\perp}^2\right). \quad (11)$$

Consequently, at the very point of synchronism, the solution of (11) has the following form

$$\omega = \frac{1}{2^{2/5}}\omega_b^{4/5}\omega_H^{1/5}\beta_{\perp}^{2/5}\left(1 \pm \beta_{\parallel} - \frac{1}{2}\beta_{\perp}^2\right)^{1/5} e^{i\frac{2\pi(m+1/2)}{5}}, \quad m = 0, 1, 2, 3, 4. \quad (12)$$

3. We shall attempt to connect the plasma instability under consideration /2051 with the observed density inhomogeneities. It follows from (7) that the characteristic dimensions of the unstable density perturbations are

$$\frac{\pi(1-\beta_{\parallel})}{\omega_H/v_{\parallel}} \lesssim l \lesssim \frac{\pi(1+\beta_{\parallel})}{\omega_H/v_{\parallel}}. \quad (13)$$

According to the data obtained in [9], the time required for the electrons to move from the Sun to the Earth is on the order of $2.4 \cdot 10^3$ sec. It thus follows that $\beta_{\parallel} \approx 0.27$. In (13), assuming the values of the magnetic field according to the data in [13] $H_0 = 10^{-5} - 10^{-4}$ gauss, we obtain

$$1{,}2 \cdot 10^7\ см \lesssim l \lesssim 2 \cdot 10^8\ см,$$

which closely coincides with the experimental data [3 - 6].

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